Design and Analysis of Capacitive Power Transfer System with and without the Impedance Matching Circuit

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Article Info	ABSTRACT
	This paper presents the design and analysis of a relatively new wireless power transfer technique using capacitive coupling, named Capacitive power transfer (CPT). In general, CPT system has been introduced as an attractive alternative to the former inductive coupling method. This is because CPT uses lesser number of components, simpler topology, enhanced EMI performance and better strength to surrounding metallic elements. In this work, aluminium sheet is used as a capacitive coupling at transmitter and receiver side. Moreover, a Class-E resonant inverter together with $\pi 1a$ impedance matching network has been proposed because of its ability to perform the dc-to-ac inversion well. It helps the CPT system to achieve maximum power transfer. The CPT system is designed and simulated by using MATLAB/Simulink software. The validity of the proposed concept is then verified by conducting a laboratory experimental of CPT system. The proposed system able to generate a 9.5W output power through a combined interface capacitance of 2.44nF, at an operating frequency of 1MHz, with 95.10% efficiency. The proposed CPT system with impedance matching network also allows load variation in the range of $\pm 20\%$ from its nominal value while maintaining the efficiency over 90%.

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1. INTRODUCTION

As part of the promising wireless power transfer system, capacitive power transfer (CPT) has been one of the major researches in building sustainable engineering system nowadays. Other than CPT, Inductive Power Transfer (IPT) [1], [2] and Acoustic Energy Transfer (AET) are also available [3], [4], [5]. The major difference of these types of wireless power transfer system is in terms of the coupling between transmitter and receiver whereby CPT uses electric field propagation [6], [7] while IPT uses magnetic field transfer [8], [9] and propagation of sound waves is the method used in AET [10], [4].

Some of the weaknesses of inductive power transfer which succeeded to be enhanced by CPT include unable to penetrate metal shielding due to low anti-interference ability of the magnetic field, and also larger eddy current produced by IPT thus indicate higher losses [11]. Strong anti-interference can reduce energy loss and electromagnetic interference, besides enable the device to work in saturated or intense magnetic fields environment.

Based on Figure 1, a CPT system consists of two major parts which are the transmitting unit and the receiving unit and is separated by a medium i.e air/skin/paper/etc. Building CPT system by using class E inverter is, at the moment, the most reliable method for higher frequency [12], [13], [14]. Moreover, this type of inverter is also used since it has simple topology and a very high efficiency achieved in return because one of the characteristics of class E is that it is able to achieve 100% switching condition known as Zero-Voltage

Switching (ZVS). During time interval, the switch current and voltage waveforms must not be overlapped throughout the switching time intervals thus produce highly efficient system since switching losses are virtually zero, provided the components' values are suitably chosen. The basic idea of a CPT system is as sketched in Figure 1.
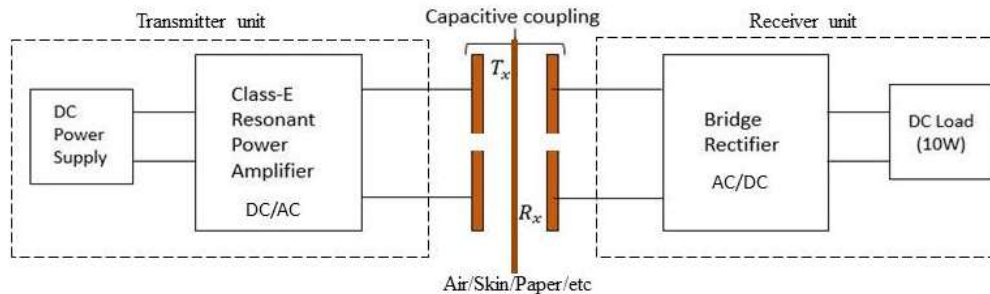

Figure 1. Basic CPT System

Apart from its advantages, CPT is currently having major issue on the efficiency as separation distance is increasing. This can be clearly shown in [15] whereby in order to achieve efficiency of 98.44%, the gap between the capacitive coupling is as near as less than 1mm for basic circuit configuration with class E inverter. Besides, there was also an analysis regarding gap distance which concluded that as distance increases, the efficiency of the system represented by output voltage is tremendously decreases exponentially shown in Figure 2.
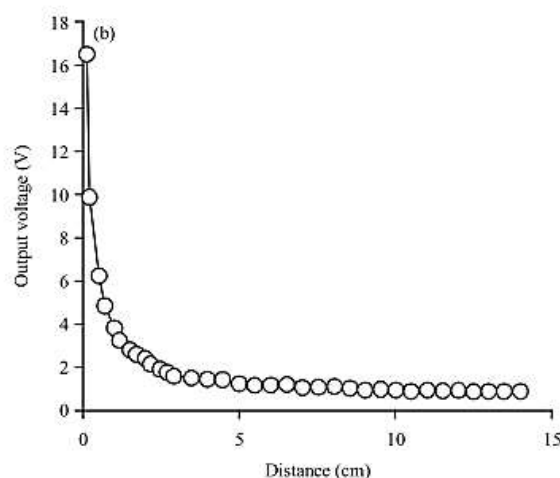

Figure 2. Output voltage decreases tremendously and distance increases [15]

Realising the issue of system's efficiency, this work intended to propose class E circuit with the addition of an impedance matching circuit. This circuit is mainly added to improve efficiency of the particular system by stabilising it and eventually sustain higher output power. Impedance matching of work in [16] used to maximise the amount of power extracted in a power conditioning circuit. In another work [17], by using impedance matching, the particular work achieved efficiency as high as 95.44% while still able to produce a stable sinusoidal signal to drive the capacitive coupling based on flat rectangular copper plates, and operated at 1MHz. The contribution of this paper can be brief as follows:
a. This paper focuses on designing a CPT system based on Class-E resonant inverter topology with aluminum sheets acting as capacitive plates. The obtained efficiency is 95.1% with 12V dc input supply, and operated at 1MHz to produce a stable sinusoidal signal across the load. The Class-E resonant

inverter with impedance matching network is also proposed to allow load variation in the range of $\pm20\%$ from its nominal value.

b. Efficiency of the CPT system is maintained over 90% with smaller plates' size with the introduction of the $\pi1a$ impedance matching network.

c. The effects on output power performance are analysed and being proved by comparing both conditions of the circuit i.e non-matching and with $\pi1a$ matching network.

2.   IMPEDANCE MATCHING NETWORK

A good system design is defined as a system which has a high output power and is able to achieve almost 100% efficiency. Thus the purpose of an impedance matching in an ordinary circuit is to provide maximum power transfer between the source and its load [18]. This is especially vital if one deals with low amplitude signals. The work also highlighted two main reasons of having an impedance matching circuit. First, is to have better power efficiency, and second, is to act as a device protection. The impedance matching circuit is added before the resistive load, as shown in Figure 3.
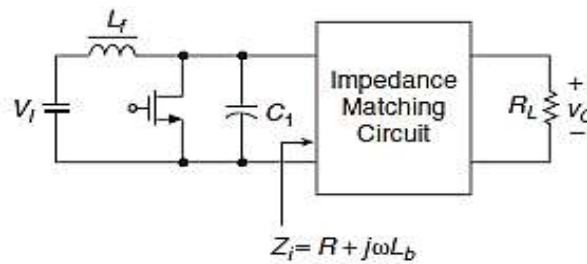

Figure 3. Block diagram of the Class E amplifier with impedance matching resonant circuit [8]

According to [19], [20] there are four types of impedance matching networks namely $\pi1a, \pi2a, \pi1b$ and $\pi4a$; see Figure 4.
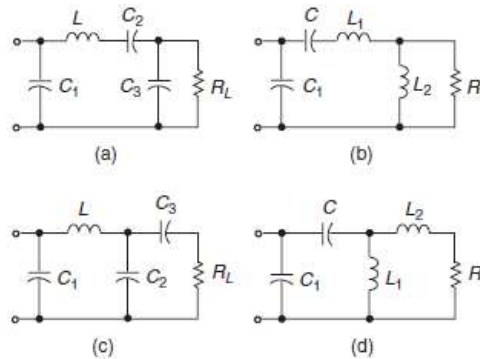

Figure 4. Different types of impedance matching networks introduced by Marian et.al. (a) Resonant circuit $\pi1a$. (b) Resonant circuit $\pi2a$. (c) Resonant circuit $\pi1b$. (d) Resonant circuit $\pi4a$ [19], [20].

All of these designs have different characteristics in terms of circuit configurations and also the measurement for the components values. Figure 4 (a) and (c) focus on the reactance of the capacitor C, while (b) and (d) are concerning on the reactance of the inductor L. In [17], authors utilized $\pi1b$ as their matching circuit to enhance output power of the existing capacitive power transfer system. As a result, when powered by 12V dc, the Class-E resonant inverter with matching network efficiency yields 95.44%. To note here, the authors in [17] used copper plates as their coupling.

On top of the above type of impedance matching techniques, realizing the need to achieve automatic current sharing for multi-phase resonant converters through matching the input impedance of each phase, authors in [21] proposed Passive Impedance Matching (PIM) in their work. Thorough this PIM approach, the

input impedances of each phase are more balance under virtual positive and negative resistor's function. With the integration of PIM into the CPT systems, the experimental results showed that the resonant current sharing error reduced by 63 times which is around 0.44% at 600W total load power.

In this work, we proposed π1a impedance matching circuit since the matching provides downward impedance transformation, and the added capacitor which is in parallel with the resistive load can maintain the efficiency of the circuit as series capacitor C_2 later modified to capacitive coupling plates to fit the actual CPT system.

3.   MAIN RESULTS
3.1. CPT System without Impedance Matching Network

The CPT system is first designed without any impedance matching circuit. This is important in order to study and analyze the performance of the circuit without impedance matching. If the performance is not satisfactory then the matching circuit can be proposed to the system. The CPT system with Class E inverter is as shown in Figure 5.
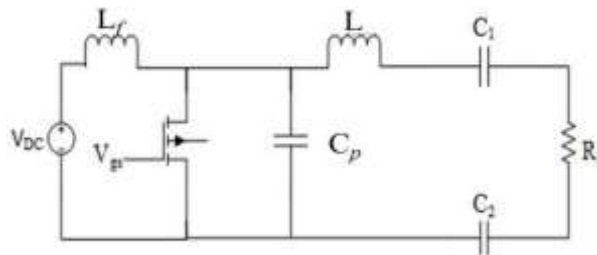

Figure 5. CPT system with Class E inverter

The components value of the circuit are derived from [19] and given as follows:

$$\text{Load resistor, } R_L: R_L = \frac{8}{\pi^2 + 4}\left[\frac{Vi^2}{PRi}\right] \tag{1}$$

$$\text{Series inductor, } L: L = \frac{Q_L R_i}{\omega} \tag{2}$$

$$\text{Shunt capacitor, } Cp: Cp = \frac{8}{\pi(\pi^2 + 4)\omega Ri} \tag{3}$$

$$\text{The series capacitor, } C: C = \frac{1}{\omega Ri\left[Q_L - \frac{\pi(\pi^2-4)}{16}\right]} \tag{4}$$

$$\text{The choke inductor, } L_f: L_f = 2\left[\frac{\pi^2}{4} + 1\right]\frac{Ri}{f} \tag{5}$$

Based on Figure 5, the basic circuit configuration of class E inverter consists of a power MOSFET operates as a switch, a L-C-R_L series-resonant circuit, a shunt capacitor C_1, and a choke inductor L_f. The switch turns on and off at the frequency $f = \frac{\omega}{(2\pi)}$ determined by a MOSFET driver. The transistor output capacitance, the choke parasitic capacitance, and stray capacitances are included in the shunt capacitance C_1. All of the capacitance C_1 can be supplied by the overall shunt parasitic capacitance for high operating frequencies.

Besides, resistor R_i is an AC load. The choke inductance L_f is assumed to be high enough so that the AC ripple on the DC supply current I_I can be ignored. A small inductance with a large current ripple is also possible. When the switch is ON, the resonant circuit consists of L, C, and R_i because the capacitance $C_1$is short-circuited by the switch. However when the switch if OFF, the resonant circuit consists of C_1, L, C, and R_i are connected in series [19]. Furthermore, in this work, the series capacitors are placed at both sides (forward and reverse) in order to ensure the resonant composition network [11]. Furthermore, the function of a choke inductor in the Class E circuit is to distinguish DC and the AC. Other than that, in order to determine the performance of the circuit, the output voltage and power can be determined as follows:

Amplitude of the output voltage,

$$V_{Rim} = \frac{4}{\sqrt{\pi^2 + 4}}[Vi]$$

(6)

Output power of the system is given by,

$$P_{Ri} = \frac{V_{Rim}^2}{2R_i}$$

(7)

3.1.1. Simulation Works for Circuit without Impedance Matching
Figure 6 shows the simulation of a complete system without impedance matching network.
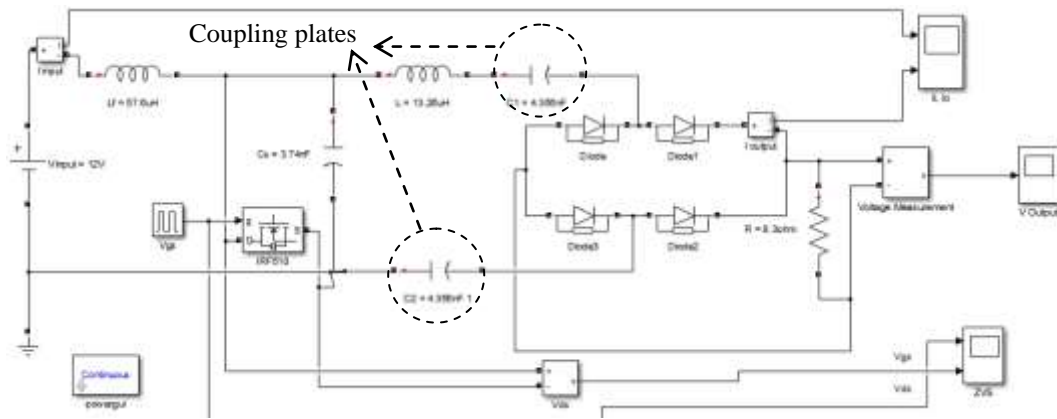

Figure 6. Complete CPT system without impedance matching circuit

Based on Equations 1-5, the following components' values are obtained, shown in Table 1.

Table 1. Calculated components' values for Class E Design Specification for CPT System without impedance matching network

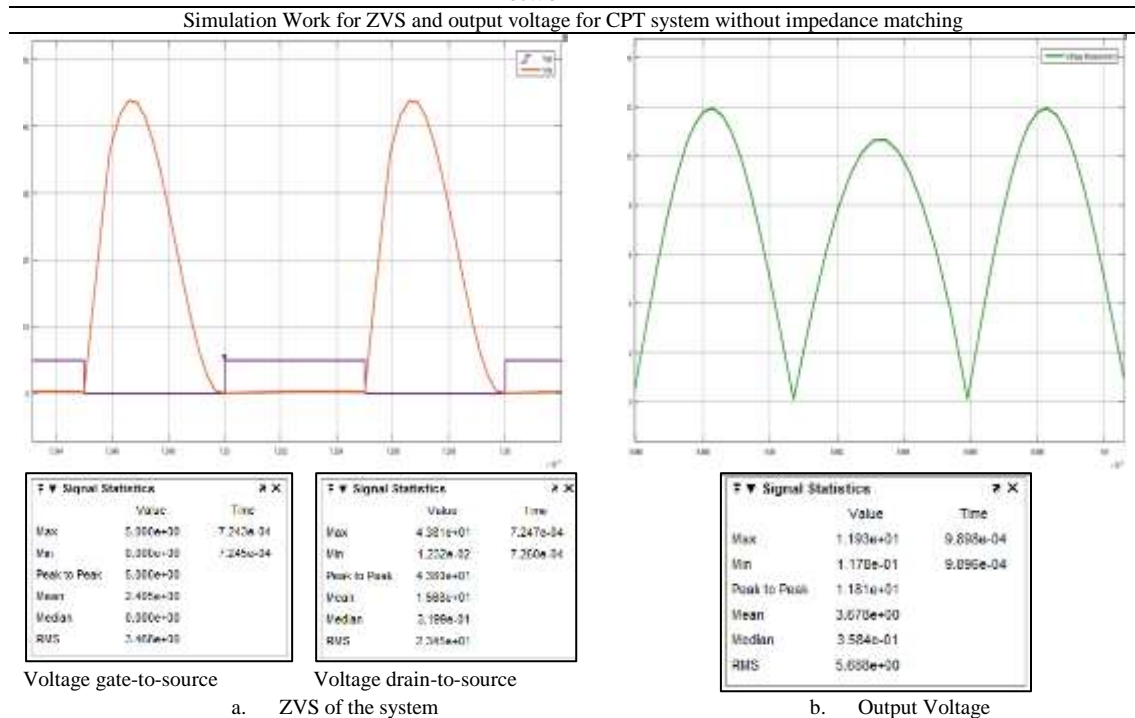| Specification	Value
Load resistance, R_L	8.31Ω
Series inductor, L	13.26μH
Shunt capacitor, Cs	3.74nF
Series capacitor, C_1 and C_2	4.356nF
Choke inductor, L_f	57.6μH

Table 1 tabulated the calculated the value of parameters for basic class E CPT system in which no impedance matching network is existed. Besides, following Table 2 shows the comparison of components' values for the basic CPT system.

Table 2. Comparison for values of components used for CPT circuit without $\pi 1a$ matching network

	CPT System without impedance matching		
	Calculation	Simulation	Experimental work
L_{choke}	57.6μH	57.6μH	100μH
C_{Shunt}	3.52nF	3.75nF	0.91nF
L_{Series}	13.23μH	13.26μH	33μH
C_{Series} (C_1 and C_2)	2.17nF	2.178nF	Capacitive coupling 0.21m x 0.24m (4.07nF)
R_L	8.31Ω	8.3Ω	8.2Ω

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From Table 2, it can be seen that experimentally, the values of series capacitors C_1 and C_2 is 4.07nF (been multiplied since the capacitors are at both forward and reverse side of the system) and represented by a capacitive coupling of 0.21m x 0.24m. As part of the work, the simulation results for ZVS and the output voltage of the CPT system is also tabulated and labeled as shown in Table 3.

Table 3. Simulation results for ZVS waveform and the output voltage for circuit without $\pi 1a$ matching network

Simulation Work for ZVS and output voltage for CPT system without impedance matching

Voltage gate-to-source   Voltage drain-to-source

a.   ZVS of the system   b.   Output Voltage

Referring to the ZVS condition of the simulation is achieved with the V_{ds} value of 43.81V. Meanwhile the output voltage of the simulation as shown in Table 3(b) is a DC waveform.

3.1.2. Experimental Works for Circuit without Impedance Matching Network

CPT system without impedance matching circuit is as shown in Figure 7. For this section, the size of the capacitance plate represented by two pairs of aluminum sheets is 0.21m x 0.24m which is equal to 4.07nF, as shown in Figure 8.
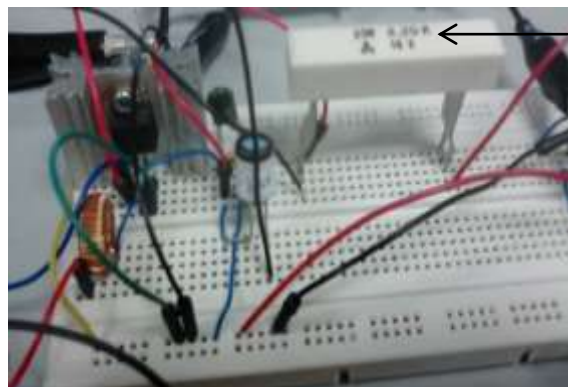
Resistive load, R_L

Figure 7. Class E circuit without impedance matching network, together with the resistive load, R_L
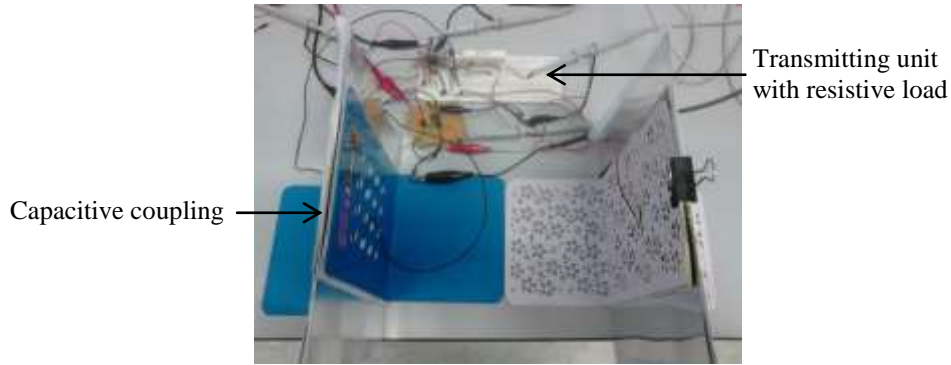
Figure 8. Whole circuit configuration including the capacitive coupling

The aluminium sheet is separated by a sheet of regular A4 paper with thickness of 0.1mm. Besides, the results for this experimental work is as tabulated in Table 4.

Table 4. Results of experimental works for CPT system without $\pi 1a$ matching circuit

Experimental Work	
a. ZVS of the system	b. Output Voltage
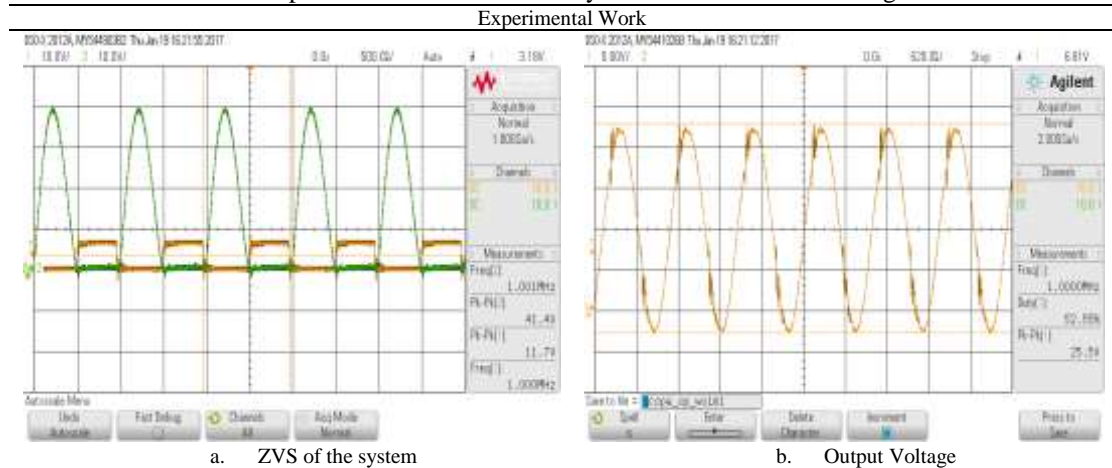
By referring to Table 5, ZVS of the built system is recorded in (a) while the outcome of the system represented by the output voltage is as shown in (b). Furthermore, there are also detailed results in Table 5 which has been made by comparing the results for all three parts done for this work, as follows:

Table 5. Details for the results of CPT circuitry system without impedance matching network

	Calculation	Experimental work
V_{in} , V	12.00	12.00
V_{out} , V (pk-pk)	25.78	25.50
P_{out} , W	9.98	9.79
Efficiency, %	99.90	97.90

Table 5 explained the results comparison between calculation and experimental works. The experimental work has shown the reliability of Class E CPT system as it achieved almost perfect results, nearly 98% efficiency. The V_{out} tabulated in the table is concerning on the peak-to-peak values, and measured at the resistive load. The output power, P_{out} for the work is measured by the formula in Equation (7), and the experimental work yields 9.79W instead of 9.98W desired by calculation. This is due to environmental condition as the experiment done in a normal laboratory. Besides, the components also have their ratings which contributes to the lower output yielded. Moreover, the simulation works of the system displayed a complete system including the rectifier thus the DC waveform of the output voltage. Whereas for

experimental side, this work is prepared without inserting rectifier part in order to focus on the ZVS condition and the output voltage, and that explained the AC shape of the waveform.

3.2. CPT System with Impedance Matching Network

This enhanced CPT system is begun with the simulation work. In order to do this, the π1a impedance matching circuit has been utilized by adding a capacitor parallel to the load. As mentioned before, there are several types of matching outlined by [19] and one of them is by tapping the resonant capacitance C to accomplish the impedance transformation, as shown in circuit configuration of π1a impedance matching circuit as in Figure 4(a). The circuit configuration of class E inverter with the π1a impedance matching network is as in Figure 9.
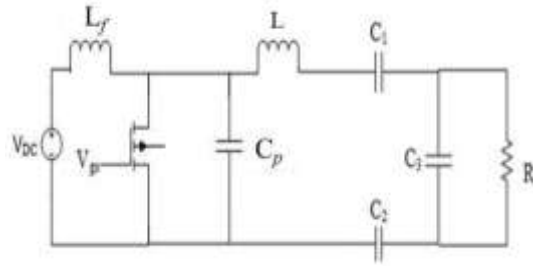

Figure 9. CPT system consisting of class E inverter with π1a impedance matching network

Besides, as the circuit enhanced, components' values for this circuit, together with the value of the newly-added capacitor C_3 which acted as an impedance matching network, also have to be calculated by using new series of Equations [19], as explained in (8) to (15):

The series equivalent resistance R_S:

$$RS = \frac{8}{\pi^2 + 4} \frac{V_I^2}{P_{Ri}} \approx 0.5768 \frac{V_I^2}{P_{Ri}} \tag{8}$$

The reactance factor for the Ri-C_3 and R_S-C_S equivalent two-terminal networks is

$$q = \frac{R_i}{X_{C_3}} = \frac{X_{Cs}}{R_S} \tag{9}$$

Besides, resistances Rs and Ri as well as the reactance X_{Cs} and X_{C_3} are also interrelated by

$$R_s = \frac{R_i}{1 + q^2} = \frac{R_i}{1 + \left(\frac{R_i}{X_{C3}}\right)^2} \tag{10}$$

And

$$X_{Cs} = \frac{X_{C3}}{1 + \frac{1}{q^2}} = \frac{X_{C3}}{1 + \left(\frac{X_{C3}}{R_i}\right)^2} \tag{11}$$

Rearrangement of (10) yield to

$$q = \sqrt{\frac{Ri}{Rs} - 1} \tag{12}$$

Substitution of (12) into (9) gives

$$X_{Cs} = R_s \sqrt{\frac{Ri}{Rs} - 1} \tag{13}$$

Later, one arrives at

$$X_{C2} = \frac{1}{\omega C_2} = X_C - XC_s = R_s \left[Q_L - \frac{\pi(\pi^2 - 4)}{16} \right] - qRs = \left[Q_L - \frac{\pi(\pi^2 - 4)}{16} - \sqrt{\frac{Ri}{Rs} - 1} \right] \tag{14}$$

From (9) and (12),

$$X_{C3} = \frac{1}{\omega C_3} = \frac{R_i}{q} = \frac{R_i}{\sqrt{\frac{Ri}{Rs} - 1}} \tag{15}$$

It follows from (15) that the resistances of circuit shown in Figure 4(a) can satisfy the inequality

$$R_s < R_i$$

Suboptimum operation is obtained for

$$0 \leq R_{s(sub)} < R_s .$$

This corresponds to

$$R_i \leq R_{i(sub)} < \infty.$$

By referring to Equation 8, V_I, P_{Ri}, and R_i are dependent quantities. The load resistance is given and is different from that given in (8) for many applications available in the market. Therefore, there is a need for matching circuits that provide impedance transformation, as the purpose of an impedance matching circuit is to ensure and to provide impedance transformation downwards or upwards regardless the load resistances [22]. After all new values of the components including impedance matching network, capacitor C_3 has been figured out, they were all been tabulated as in Table 6.

Table 6. Calculated components' values for Class E design specification with the existence of $\pi 1a$ impedance matching network

Specification	Value
Load resistance, R_L	8.31Ω
Series inductor, L	13.12μH
Shunt capacitor, Cs	3.7nF
Series capacitor, C_1 and C_2	4.6nF
Choke inductor, L_f	57.6μH
Impedance Matching, C_3	1nF

The calculated impedance matching network value of C_3 is 1nF. Moreover, as Table 1 and Table 6 to be compared, there are different values for the same components of series inductor L, the shunt capacitor Cs, and the series capacitor C_1 and C_2. This is due to different equations that have been used to calculate the components' values, as displayed in Equations (8) to (15).

3.2.1. Simulation Works of Circuit with Impedance Matching Network

By using MATLAB Simulink, a simulation of CPT system including an impedance matching network is constructed as is Figure 10. For this simulation circuit, a capacitor is placed parallel to the resistive load and acts as an impedance matching network. Besides, there is also a pair of capacitors at the forward and reserve side of the circuit. These capacitors are being modified into two pairs of capacitive couplings in the experimental works, shown in Figure 11(b). Moreover, after the simulation work is being

accomplished by inserting suitable values of the components, the desired results are tabulated in Table 7. The two main concern of the simulation work is the waveforms of zero-voltage switching (ZVS) condition, and the output voltage of the system.
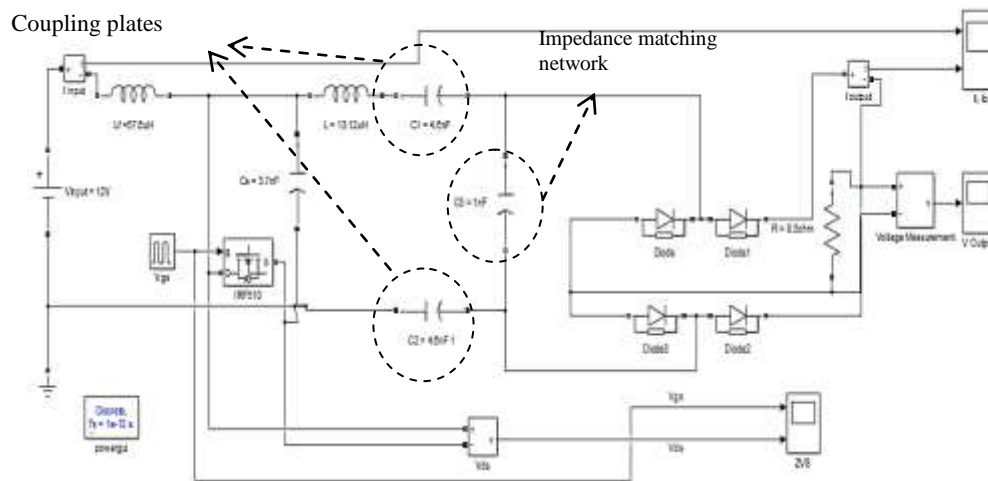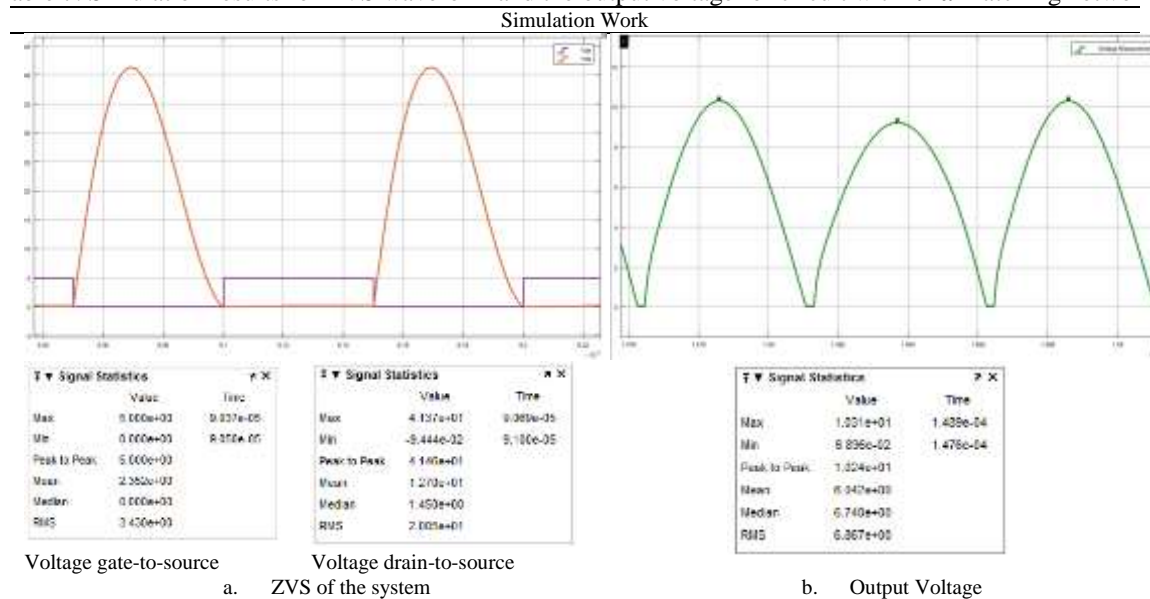

Figure 10. Simulation diagram for a complete CPT system including π1a impedance matching network

Table 7. Simulation results for ZVS waveform and the output voltage for circuit with $\pi 1a$ matching network

As mentioned previously, the waveform for output voltage is in DC since the system is completely constructed with the rectifier. However the experimental work, as shown in Table 8, is prepared up to the impedance matching network without the rectifier part since this work is focusing on the ZVS condition and the output voltage, thus the AC waveform presented.

3.2.2. Experimental Works of the CPT System with Impedance Matching
Moreover, the work is later advanced by adding an impedance matching circuit represented by a capacitor. Figure 11 shows the experimental work of the system with the existence of π1a impedance matching network. By referring to Figure 11, after adding the impedance matching, the size of capacitor plates becoming smaller to 0.15m x 0.16m which is equivalent to 2.44nF, almost half of the value before. This shows that the impedance matching is able to reduce the size of capacitive coupling while still

maintaining the output of the system by allowing power transmission through them. The impedance matching network has enhanced several things including the output values for the circuit of the CPT system. Table 8 explained the results of the experiment by taking into account the values of components for the system.
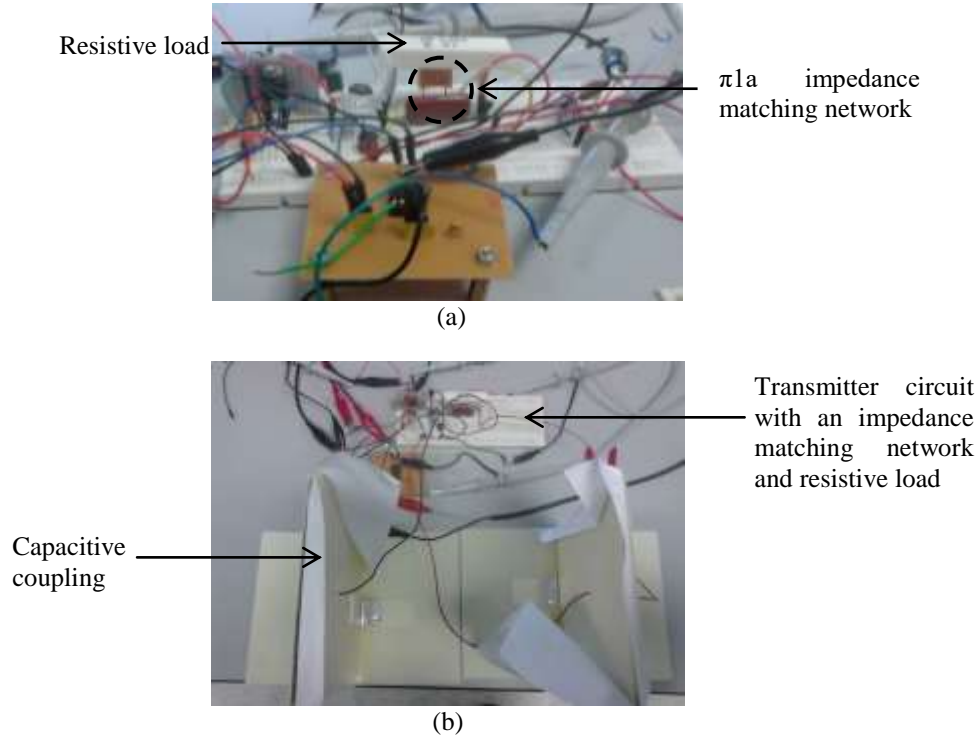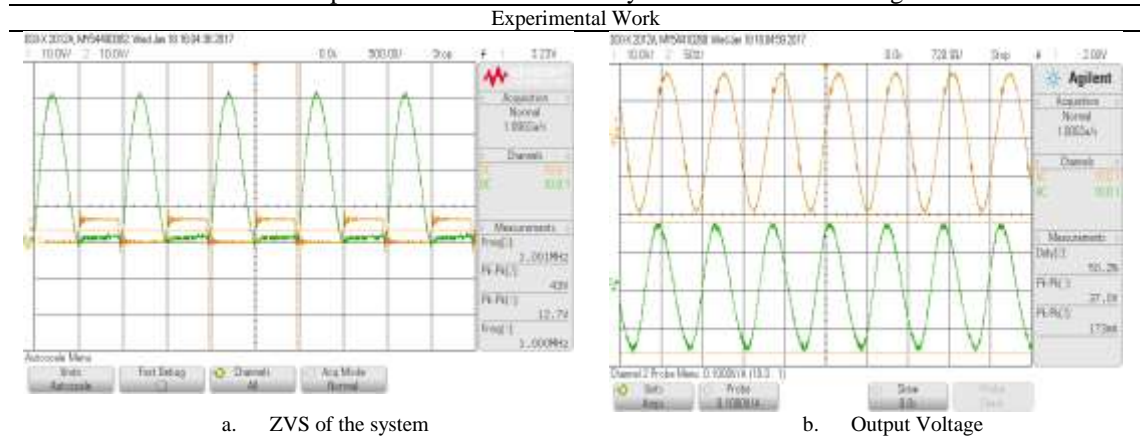

(a)

(b)

Figure 11(a) and (b). Circuit representation of CPT system with an existence of $\pi 1a$ impedance matching network

Table 8. Results of experimental works for CPT system with $\pi 1a$ matching circuit

Experimental Work	
a. ZVS of the system	b. Output Voltage

By referring to Table 8, ZVS condition of the CPT system is recorded in (a) while the outcome of the system represented by the output voltage is as shown in (b- upper part). In conjunction to the impedance matching network, the detailed components' values for calculation, simulation, and experimental works for CPT system with π1a impedance matching network is as explained in Table 9.

Table 9. Values of components used for CPT circuit with $\pi 1a$ impedance matching network

CPT System with π1a impedance matching network			
	Calculation	Simulation	Experimental work
L_{choke}	57.63µH	57.6µH	100µH
C_{Shunt}	3.52nF	3.52nF	52.1pF
L_{Series}	13.23µH	13.12µH	60.3µH
C_{Series} (C_2)	2.16nF	2.3nF	Capacitive coupling 0.15m x 0.16m (2.44nF)
R_L	16.6Ω	20Ω	18Ω
Impedance matching (C_3)	9.6nF	1nF	9.8nF

Based on Table 9, for experimental work, the aluminium sheets were utilized to replace the series capacitors as the forward and reverse capacitive couplings respectively. Moreover, as for results comparison, the calculated values are almost the same as simulated ones, except for the impedance matching C_3. However, when compared with the experimented values, they displayed huge difference due to imperfect environmental situation since it is not vacuumed and the components ratings. The experiment is also done by using a breadboard which may contribute to the significant values difference. Finally, the output results of the CPT system with $\pi 1a$ impedance matching circuit are as tabulated in Table 10.

Table 10. Details for the results of CPT circuitry system with $\pi 1a$ impedance matching network

	Calculation	Experimental
$V_{in,}$ V	12.00	12.00
$V_{out,}$ V (pk-pk)	37.44	37.00
$P_{out,}$ W	9.73	9.51
Efficiency, %	97.30	95.10

By referring to Table 10, the experimental part of the CPT system produced 37V, which is 0.44V lesser than the calculated value. This situation more or less affected the output power of the system experimentally to be 0.22W lesser than calculation value which is 9.73W.

3.2.3. Aluminium Sheets as Capacitive Couplings

This work uses aluminium sheet as the capacitive coupling. The reason of utilizing this type of material is because aluminium has advantages in terms of its excellent corrosion resistance, and good thermal and electrical conductivity. As proved and explained in previous sections, the aluminium sheets' size for the CPT system is getting smaller by the existence of an impedance matching network, as shown in Figure 12. This is due to the recalculation of components values by using equations (8-15) and by adding an extra capacitor as impedance matching, the desired output is achieved and maintained with smaller size of capacitive plates. The value of the capacitive coupling is initially 0.21m x 0.24m, which is equal to 4.07nF. However, after inserting the extra capacitor as impedance matching network, the value of capacitive coupling is 0.15m x 0.16m that is equal to 2.44nF.
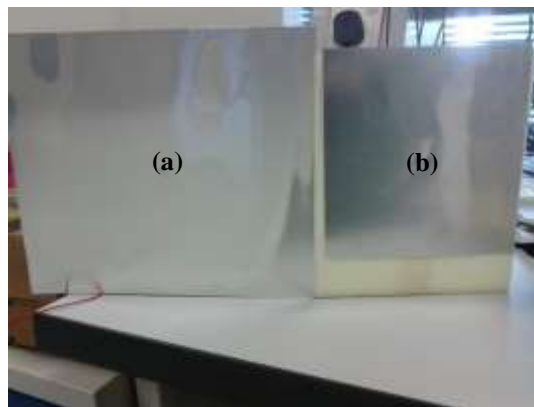

Figure 12. Comparison of couplings' size between CPT circuit without $\pi 1a$ impedance matching network (a) and the circuit with $\pi 1a$ impedance matching network (b).

It can be seen that there is major difference by referring to Figure 12, as the diameter of the couplings is being compared. This shows that the presence of an impedance matching network has significant change towards the whole CPT system particularly on the maintainance of ZVS and also the output voltage and power which are the two concerns in this work.

4. CONCLUSION AND FUTURE WORKS

This paper proposes an impedance matching circuit for a CPT system. The power output for both conditions is analyzed, which indicate the circuit without impedance matching and with the extra circuitry part. A prototype of the CPT system with an impedance matching network is designed and implemented to validate the theoretical results of the improvised circuit system. Finally, the normal circuit and with $\pi 1a$ impedance matching circuit topologies are compared in terms of power, size of capacitive plates, and efficiency. The efficiency of the system after the introduction of $\pi 1a$ matching is 95.10%. It shows that the installation of $\pi 1a$ matching circuit can maintain the efficiency while using smaller size of capacitive plates. For future works, the self-tuning circuit will be proposed into the CPT system in order to enhance the power output and the efficiency by using phase locked-loop (PLL) and later with a PID controller.

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